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Case Study: Multipollutant Indoor Air Quality Study of 300 Homes in Kingston/Harriman, Tennessee

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KEY WORDS: residential field studies, multipollutant studies, nitrogen dioxide, respirable particulates, radon, formaldehyde, polynuclear aromatic hydrocarbons, microorganisms, bioaerosols, Kingston/Harriman

Over the past two decades, substantial progress has been made in improving many areas of outdoor air quality. The latter part of this period saw an increased awareness of the important contribution that indoor air quality makes to the total exposure of the public to many pollutants. Frequently, higher pollutant concentrations indoors and the large fraction of time spent indoors are principal factors responsible for the higher indoor exposures. Current estimates of indoor pollutant exposures from residential environments are based on field studies from a limited number of sites around the country. Much additional work remains to be done before an adequate picture of residential indoor air quality in the United

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States is formed. This case study is based on one of the most comprehensive residential field studies conducted to date. It provides an example design and protocol for monitoring residential indoor air quality.

The Harvard School of Public Health (HSPH) has been investigating the relationship between air quality and respiratory health for over a decade [*1*]. Awareness of the significance of indoor exposures has led HSPH researchers to begin a new phase of their multiyear, multicity study. This phase measures indoor levels of important pollutants related to acute respiratory illnesses and lung function development in school-aged children [*2*]. One of the cities in the Harvard study is Kingston/Harriman, Tennessee. These East Tennessee communities have participated in various components of the HSPH studies for nearly a decade. During 1985–86, indoor air quality measurements were performed in more than 300 Kingston/Harriman homes. With the support of several sponsors, additional research was performed in Kingston/Harriman to supplement the "core" monitoring being performed in each city in the HSPH multicity design.

Study Design

As part of the larger HSPH indoor air quality study, the Kingston/Harriman study has many design aspects in common with the other cities in the project. However, several aspects of the design are unique to this study. In the following two sections, the common design features are described, as well as those unique to the Kingston/Harriman study. A brief description of the larger six-city study is provided for completeness before emphasis is placed on the more unique aspects of the Kingston/Harriman study.

Harvard Six-City Study

The Harvard Six-City Study is an epidemiologic investigation of the relationship between air quality and lung function and development, primarily in children, in six cities throughout the United States. HSPH, under the sponsorship of the National Institute of Environmental Health Sciences (NIEHS), the Electric Power Research Institute (EPRI), and the Environmental Protection Agency (EPA), has been conducting this series of studies for about a decade. The program assesses the air quality in six cities in the United States that reflect a range of outdoor air quality. The cities are Kingston/Harriman, Tennessee; Portage, Wisconsin; St. Louis, Missouri; Steubenville, Ohio; Topeka, Kansas; and Watertown, Massachusetts. Originally, exposure data came from ambient air monitoring stations in each city, and the health data came from spirometry tests and a health questionnaire. At present, the focus of the HSPH study is shifting to the indoor environment. The new aspect of the study, the Indoor Air Quality/Health Study, calls for measuring the indoor air quality in approximately 300 houses in each city, while acute respiratory health data are being collected from a child in each study house. The six cities, representing 1800 homes, will be studied over a four-year period with approximately two cities being monitored during any one year.

Each home selected for participation in the six-city indoor air quality study must have resident at least one school child from the health study. The indoor air quality study is focused primarily on combustion-related pollutants. The protocol for the six-city study generally calls for a 2 by 2 design containing sample cells for homes with parental cigarette smoking, homes with gas stoves, homes with neither, and homes with both. Air quality measurements are designed to provide an assessment of nitrogen dioxide levels, respirable particulate levels, and the average air exchange rate and water vapor levels during the air quality measurements. Measurements are performed over two consecutive one-week periods in each house, once during the winter and again the next summer. A daily record of the respiratory health of the participating grade-school child is maintained during the full year.

Kingston/Harriman Study

An extensive characterization of the indoor air quality in 300 homes in Kingston/Harriman, Tennessee, has grown out of a joint interest by the Harvard School of Public Health, the Tennessee Valley Authority (TVA), EPRI, the Consumer Product Safety Commission (CPSC), and Oak Ridge National Laboratory (ORNL) in maximizing the indoor air quality information that could be obtained from the Kingston/Harriman phase of the Harvard Indoor Air Quality/Health Study. Additional indoor air quality research has supplemented the "core" set of measurements being performed by the HSPH on air quality and respiratory health. Within the limitations that additional characterization of indoor air quality, weatherization, and energy usage not compromise the objectives of the Harvard study and not overly burden the participating homeowners, this expanded study offered a valuable opportunity to gain additional indoor air quality information in a most cost-effective way. Much of the expense of identifying and involving the study participants, characterizing their health, and making field visits to their homes was not required for the supplemental measurements. An additional valuable asset of this collaborative research is the opportunity to investigate correlations between various components of the multifaceted study. Supplemental investigations included additional pollutants (e.g., radon, formaldehyde, polynuclear aromatic hydrocarbons, and airborne microorganisms), building factors (e.g., weatherization status), and energy use (e.g. kerosene heaters and wood stoves).

The Kingston/Harriman phase of the six-cities study provided a unique opportunity to investigate the interrelationships of wood and kerosene heater use, indoor air quality, and respiratory health in 300 homes. Because there are relatively few homes in the Kingston/Harriman area with gas appliances, the researchers agreed that this was an excellent opportunity to investigate the impact of wood-burning and kerosene heater use by substituting these sources of fuel for the gas component in the six-city study design. A substantial fraction of homes in the area use wood or kerosene, either as the primary heating fuel or as a secondary source of heating. The study population was stratified on three different pollutant sources potentially present in the homes: smokers, kerosene heaters, and wood stoves. Table 1 identifies the eight groups into which the houses were classified in this 2 by 2 by 2 study design.

The study population was selected in the spring of 1984 from students in the Kingston and Harriman schools. A letter and health survey were sent home to children in the 2nd, 3rd, and 4th grades. From those that responded, 1018 were selected as a new cohort for the respiratory health component of the study. In the fall of 1985, a total of 692 letters were sent to the parents of children with homes that fit the 2 by 2 by 2 study design requesting their participation in the indoor air quality phase of the study. A follow-up phone call was made to request a response. Of the 692 families solicited, 186 (27%) were unreachable, 129 (18%) declined to be in the study, and 377 (54%) were willing to participate in the study.

TABLE 1—*Group classification code by presence of specific home characteristics.*

Group	Smoking	Kerosene Heater	Wood Stove
1	no	no	no
2	no	no	yes
3	no	yes	no
4	no	yes	yes
5	yes	no	no
6	yes	no	yes
7	yes	yes	no
8	yes	yes	yes

TABLE 2—*Summary of weekly initial setups by group code.*

Week of	Group Code								Total
	1	2	3	4	5	6	7	8	
11/11/85	3	3	2	1	2	2	3	2	18
11/18/85	2	4	2	2	3	3	1	2	19
11/25/85	1	7	0	1	2	3	5	0	19
12/02/85	2	5	5	0	2	3	3	2	22
12/09/85	2	3	7	0	4	3	3	2	24
12/30/85	2	4	1	2	2	2	2	2	17
01/06/86	1	4	2	1	2	4	2	2	18
01/13/86[b]	3	4	3	4	3	3	4	4	28
01/20/86	4	4	2	1	1	3	3	2	20
01/27/86	3	3	2	0	2	6	4	2	21
02/03/86	1	2	5	2	2	4	2	2	20
02/10/86	4	6	1	1	4	4	1	3	24
02/17/86	3	4	3	1	3	4	1	1	20
02/24/86	2	6	5	2	3	3	1	1	23
03/03/86	5	5	4	2	0	1	0	0	17
03/10/86	2	3	2	0	1	0	1	0	9
Total	40	66	46	20	36	48	36	27	319
05/12/86	0	0	1	2	1	0	0	0	4
05/19/86	6	6	5	4	4	6	4	3	38
05/26/86	2	4	2	3	3	4	4	4	26
06/02/86	1	6	2	2	4	4	4	2	25
06/09/86	2	4	3	1	3	5	3	3	24
06/16/86	1	2	4	1	3	3	4	1	19
06/23/86	0	4	4	0	2	6	3	1	20
06/30/86	3	3	2	0	3	6	4	2	23
07/07/86	6	6	2	1	1	4	2	1	23
07/14/86[c]	3	4	0	3	1	1	4	3	19
07/21/86	4	9	4	2	1	3	2	3	28
07/28/86	4	7	9	0	0	2	0	1	23
08/04/86	2	9	6	1	0	1	0	1	20
08/11/86	2	0	2	0	0	1	0	0	5
08/18/86	1	0	1	0	0	0	0	0	2
Total	37	64	47	20	26	46	34	25	299

[a] Excluding fall and spring pilot visits.
[b] Winter visit to pilot group.
[c] Summer visit to pilot group.

By mid-November of 1985, 17 (2.5%) families had reconsidered and declined participation in the study, leaving a total of 360 families willing to participate in the air quality monitoring phase. Table 2 shows the final distribution of homes that participated in each study category. Table 2 also summarizes the number of weekly visits for the winter and summer phase of the study.

Indoor air quality measurements began in the fall of 1985. The bulk of the sampling consisted of monitoring the air in the houses for two consecutive one-week periods in the winter and the summer. A total of 319 houses were monitored during the winter phase and 299 houses during the summer phase. A subset of approximately 30 houses of the 319 were sampled during the same two-week period in the fall, winter, spring, and summer. (This group of houses is referred to as the pilot group.) The initial setup weeks for the pilot sampling were: fall, 10/14/85; winter, 1/13/86; spring, 4/14/86; and summer, 7/14/86. The

pilot group was used to evaluate field protocols prior to the major field monitoring effort and to assess variation in pollutant levels in the spring and fall.

Protocols, Implementation, and Results

Specific protocols were developed for monitoring pollutants, obtaining health data, and characterizing occupant behavior and house characteristics. Measurements and information generally were obtained during one or more visits by field technicians or energy auditors through on-site interviews or inspections or by installing integrating samplers that operated over a one-week period. Passive samplers were used as much as possible because of their practicality and cost-effectiveness. Figure 1 is a photograph of a sampling rack containing several of the passive monitors used in the study. Sampling with these passive devices was conducted in the child's bedroom, the activity room (room where the child spends the major fraction of time, usually a family room, den, or living room), and the kitchen. An NO_2 sampler was placed outside each home for ambient air measurement. A subset of other measurements was also made in the school and outdoors. Samplers (except radon samplers) were placed during an initial visit to the home and exchanged for new ones a week later; the second set was picked up at the end of the second week.

Over the two-week sampling period, three visits were made to each house. The first visit was to set up the samplers, the second to exchange them, and the third to remove the second

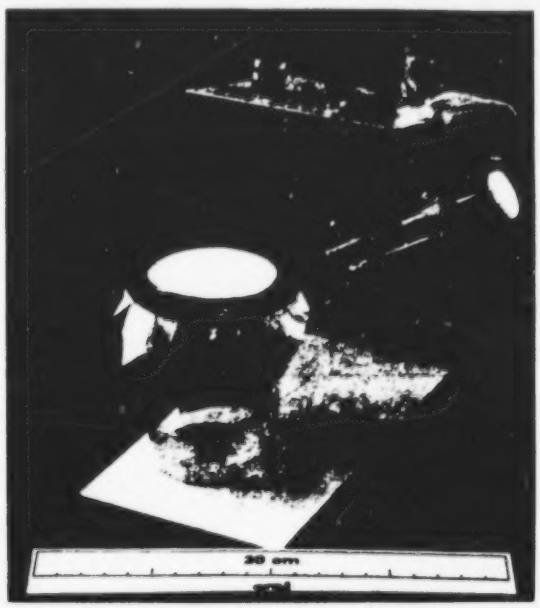

FIG. 1—*Photograph of passive samplers used in the Kingston/Harriman study. (The cup sitting on the sampling rack measures radon. The other passive samplers, from left to right, measure water vapor, perfluorocarbon tracers, polynuclear aromatic vapors, nitrogen dioxide, and formaldehyde.)*

week's samplers. Sampling was initiated in about 20 additional houses each week. Information sheets that explained the study objectives and other useful information were provided to the homeowners. Questionnaires to characterize the housing parameters (e.g., building materials, heating systems) and occupant behavior (e.g., smoking, household pets) were administered during the winter setup visit, while a follow-up questionnaire was given in the summer. These questionnaires consisted of approximately 20 pages of questions and addressed housing characteristics and occupant behavior. In an effort to keep study participants informed and interested in the study, we began devoting a portion of our quarterly *Indoor Air Study Notes*, a short newsletter sent to participants of ORNL field studies, to the Kingston/Harriman homeowners.

Details of specific measurement protocols are outlined in the following sections. Table 3 summarizes monitoring protocols used in the study.

Acute Respiratory Health Monitoring

The complementary Acute Health Study monitored the respiratory health of grade school children in the 300 homes. This component of the Kingston/Harriman study investigated the association between health and indoor pollutant exposures. Health monitoring consisted of a health questionnaire and respiratory testing plus a daily calendar of respiratory symptoms maintained by the child's parent. Figure 2 shows respiratory health codes and a typical month of data. This research component was performed entirely by HSPH.

TABLE 3—*Summary of Kingston/Harriman study protocols.*

	Sampling Period	Frequency/ Season	No. of Seasons	Method
"Core" Pollutants				
Nitrogen dioxide	1 week	2	2	passive sampler
Respirable particulates	1 week	2	2	active sampler
Water vapor	1 week	2	2	passive sampler
"Supplemental" Pollutants				
Radon	3–5 months	1	2	passive sampler
Formaldehyde	1 week	1	2	passive sampler
Polynuclear aromatic hydrocarbons	1 week	1	2	active & passive samplers
Microbial aerosols	2 min	1	2*	active sampler
Energy Use/Weatherization				
Air exchange rates	1 week	2	2	traces sources and passive samplers
Interzone air mixing	1 week	2	2	tracer sources and passive samplers
Kerosene heater substudy	1 week	8 to 10	1	passive NO_2 samplers (active monitoring in subset of 5 houses)
Questionnaires				
Weatherization audits		one time only		TVA energy auditors
Occupant behavior		one time only		survey
Housing characteristics		one time only		survey
Respiratory health calendars		daily records		calendar
Health questionnaire		one time only		survey

* Reduced sampling during winter.

SAMPLE CALENDAR: AUGUST

If your child has any of the symptoms listed below, please write the code number of that symptom in the block for that day.

A	Hoarseness	H	Ear Pain or Discharge
B	Sore Throat	J	Runny or Stuffed Nose
C	Cough	K	Burning, Aching or Red Eyes
D	Phlegm from the Chest	L	Restricted Activities
E	Pain in the Chest	N	Saw Doctor or Nurse
F	Wheezing	P	Hospitalized
G	Fever	O	Healthy or None of the Above

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
				1 O	2 O	3 O
4 O	5 O	6 O	7 J - C	8 J - C	9 J - C	10 J - C
11 O	12 O	13 O	14 O	15 O	16 O	17 O
18 O	19 O	20 O	21 O	22 O	23 O	24 O
25 O	26 O	27 O	28 O	29 O	30 O	31 O

FIG. 2—*Example of the acute respiratory health calendar used in the study.*

"Core" Air Quality Monitoring

A specific set of indoor air quality measurements is being conducted in all six cities of the Harvard study. These "core" parameters are nitrogen dioxide, particulate matter <2.5 μm (PM 2.5), air exchange rate, and water vapor. An extensive questionnaire documenting occupant behavior and house characteristics is also a part of the six-city study.

Nitrogen Dioxide—Nitrogen dioxide (NO_2) levels were measured using passive Palmes-tube type samplers exposed for one-week periods [*3*]. In addition to the three indoor sampling locations, one NO_2 sampler was located outdoors. Samplers were placed in schools during

the winter. Field placements include 5% replicate samplers and 5% field blanks. A total of 2800 samplers were used during the winter study phase with a similar number of samplers used during the summer phase. Figure 3 shows the distribution of results obtained during the winter phase of the study. Ambient air monitoring was also performed by HSPH at a central monitoring station using a chemiluminescence NO_2 monitor with concurrent sampling by the passive NO_2 samplers.

Respirable Particles—Particle samplers were obtained using a quiet, compact, constant-flow pumping system developed by HSPH [*4*]. This unit has a 2.5 μm cut size and samples respirable-size particles (PM2.5). One pumping unit can support two impactors. One sample was returned to HSPH for gravimetric and elemental analyses, and the other was retained at ORNL for analyses of polynuclear aromatic hydrocarbons. Each sampler collected particulate matter for approximately one week; operation was concurrent with the passive monitors. Air flow (4 L/min) was automatically switched between the two impactors every 15 min. An elapsed (sampling) time reading was obtained for each impactor. One pump (two samplers) was placed in the activity room for two consecutive weeks of monitoring. A total of 640 samplers were placed and returned to the laboratory for analysis during the winter study phase, with a somewhat smaller number of samples collected during the summer phase due to increased emphasis on replicate measurements. The distribution of respirable particulate levels in the study homes is presented in Fig. 4. Respirable particulate levels were also measured in some of the schools.

Water Vapor—Water vapor samples were collected using passive diffusion tubes with molecular sieve sorbent to trap the water vapor [*5*]. Weight gain of the molecular sieve is

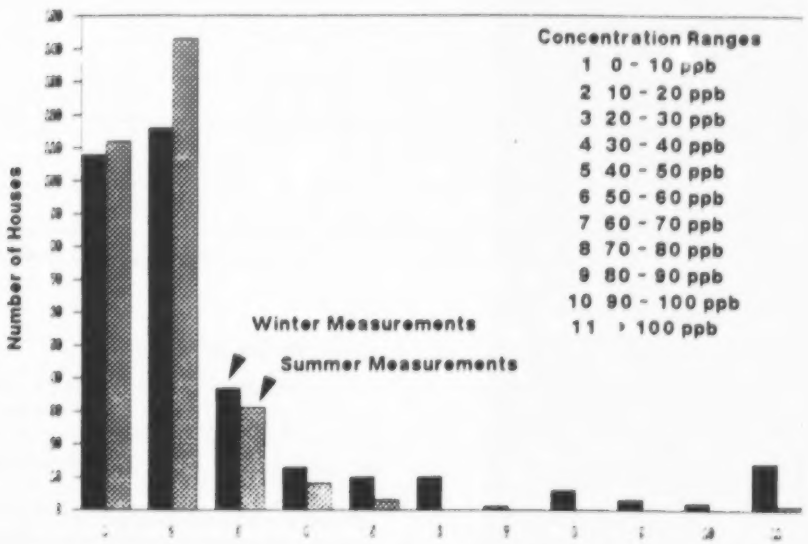
Concentration Ranges
1 0 - 10 ppb
2 10 - 20 ppb
3 20 - 30 ppb
4 30 - 40 ppb
5 40 - 50 ppb
6 50 - 60 ppb
7 60 - 70 ppb
8 70 - 80 ppb
9 80 - 90 ppb
10 90 - 100 ppb
11 > 100 ppb
Winter Measurements
Summer Measurements
Number of Houses
Nitrogen Dioxide Concentration Range

FIG. 3—*Distribution of preliminary NO_2 results (ppm).*

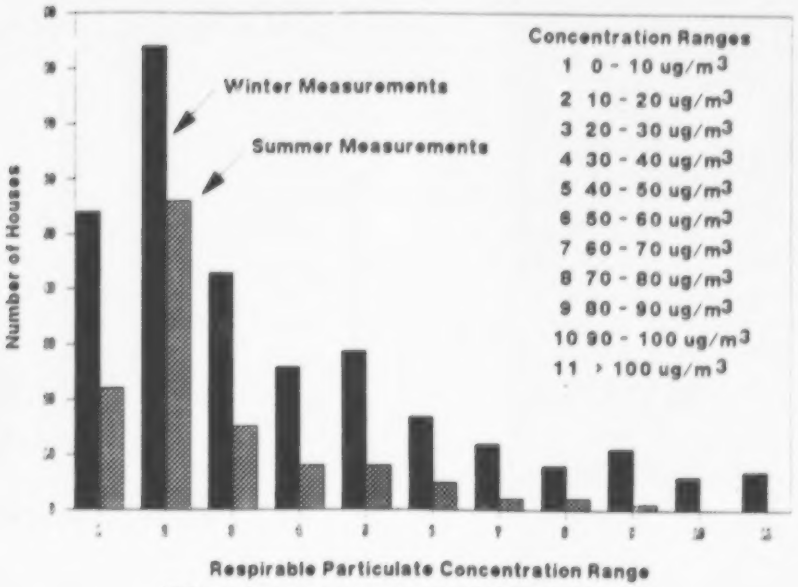
Concentration Ranges
1 0 - 10 ug/m3
2 10 - 20 ug/m3
3 20 - 30 ug/m3
4 30 - 40 ug/m3
5 40 - 50 ug/m3
6 50 - 60 ug/m3
7 60 - 70 ug/m3
8 70 - 80 ug/m3
9 80 - 90 ug/m3
10 90 - 100 ug/m3
11 > 100 ug/m3
Winter Measurements
Summer Measurements
Number of Houses
Respirable Particulate Concentration Range

FIG. 4—*Distribution of preliminary RSP results* ($\mu g/m^3$).

proportional to the integrated water vapor concentration. These sample tubes were exposed concurrently with the indoor NO_2 samplers in the activity room and returned to HSPH as a package. Field placements include 5% replicate samplers and 5% field blanks. A total of approximately 700 samplers were placed and returned to the laboratory for analysis during each phase of the study. Figure 5 shows the distribution of water vapor concentrations obtained for the winter and summer monitoring phases.

Air Exchange Rate—Average air exchange rate measurements were obtained for each one-week period that pollutant monitors were exposed. The technique used is similar to that of Dietz et al. at Brookhaven National Laboratory [6]. Small sources of perfluorocarbon tracers (PFT) were placed in the homes. Passive collection tubes (CATS), co-located with the other passive samplers, were used to sample the amount of tracer in the air. Samplers were returned to HSPH for desorption and analysis. Field placements include 5% replicate samplers and 5% field blanks. A total of 2800 samplers were placed and returned to the laboratory for analysis during the winter study phase, with a somewhat smaller number used during the summer phase. Results are not yet available for air exchange rates.

"Supplemental" Air Quality Monitoring

Radon—Measurements of radon levels were made in 250 houses during the winter phase of the study and in 285 houses during the summer phase using passive track etch monitors from Terradex Corporation (Walnut Creek, Calif.) similar to those described by Alter and Fleischer [7]. Good precision and correlation with a real-time radon monitor were obtained in a detailed assessment of these devices in an earlier work in a nearby community [8]. The

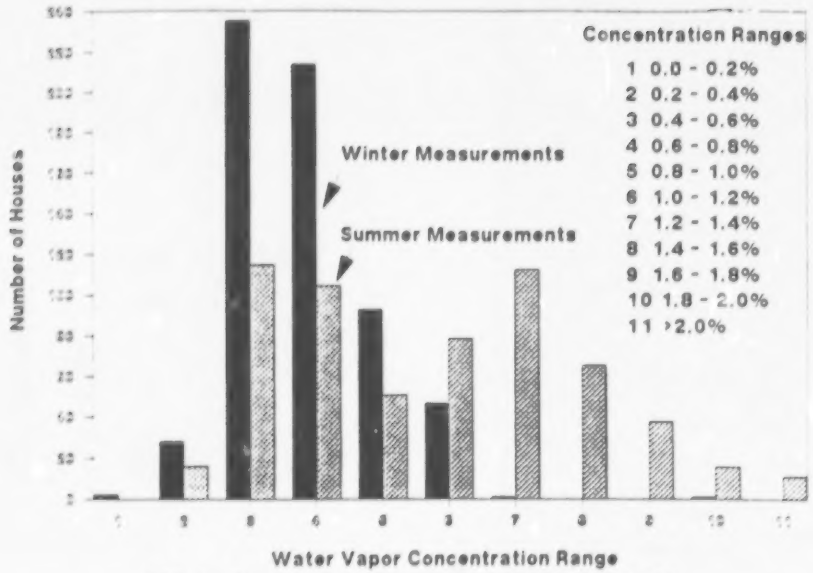

FIG. 5—*Distribution of preliminary water vapor results (wt%).*

radon monitoring device was typically placed on top of the kitchen refrigerator (chosen as a common reference point in homes, generally located on the first floor) for a period of three to five months. A total of 304 samplers were retrieved from homes during a spring exchange visit when new samplers were placed for the summer phase. In 32 homes during the winter and 40 homes during the summer, a second monitor was placed in a finished basement. Approximately 5% of the radon samplers were exposed as replicates and 5% as field blanks. Monitors were also placed in seven area schools. Most winter samplers were placed in October or November, either during the setup visits for the weekly monitors or during special visits to place the radon samplers, and retrieved during March or April. A similar process was adopted during the spring exchange. Homes with final pick-up visits for other samplers during March or April had a concurrent exchange of radon samplers. Special visits were made during April to exchange radon samplers in the remaining homes. All radon samplers were retrieved during August.

Figure 6 shows the winter and summer distribution of radon levels in the study houses. Radon concentrations in approximately 14% of houses were greater than 4 pCi/L and 6% were greater than 8 pCi/L during the winter. During the summer, approximately 5% were greater than 4 pCi/L and 1.5% were greater than 8 pCi/L. Note that these results are for measurements generally made in the kitchen and are exclusive of basement results.

Formaldehyde—Formaldehyde measurements were made with passive integrating monitors similar to those developed by Lawrence Berkeley Laboratories and described by Geisling et al. [9]. The monitors used for the study are available commercially from Air Quality Research (Berkeley, Calif.).

The measurement period coincided with the first week of monitoring for NO_2 levels, water vapor, and PFT, and the formaldehyde monitors were colocated with these passive monitors.

The monitors were generally deployed for one week in the activity room of the house. In addition to the activity room samplers, approximately 10% of the monitors were placed in the kitchen, 10% were placed in the bedroom, 5% were placed as replicates, and 5% were returned to the vendor without exposure. Formaldehyde samplers were also placed in the seven area schools. Approximately 10% of the homes had formaldehyde samplers placed during the second week of monitoring.

The distribution of formaldehyde levels for the winter season and the summer season is presented in Fig. 7. Consistent with the impact of increased temperature and humidity on many formaldehyde sources, higher levels were observed in the summer months. Approximately 5% of the homes had levels greater than 0.1 ppm during the winter, while approximately 18% had levels greater than 0.1 ppm during the summer (however, only about 6.5% were greater than 0.125 ppm).

Polynuclear Aromatic Hydrocarbons—One important class of potential indoor pollutants associated with the operation of woodburning stoves is polynuclear aromatic hydrocarbons (PNAs). Another indoor source of PNAs is cigarette smoking. A major component of the supplemental indoor air quality measurements conducted in the Kingston/Harriman study was a measurement of airborne PNA material. Both vapor phase and particulate phase PNAs were measured in the study houses.

Active and passive monitoring techniques were used to estimate indoor PNA levels. Particulate phase PNAs were sampled using the PM2.5 particle impactor developed by HSPH [*4*]. Teflon-PTFE filters were extracted and analyzed by synchronous luminescence (SL) [*10–12*]. A subset of homes were monitored with an XAD-4 sorbent tube backup to the

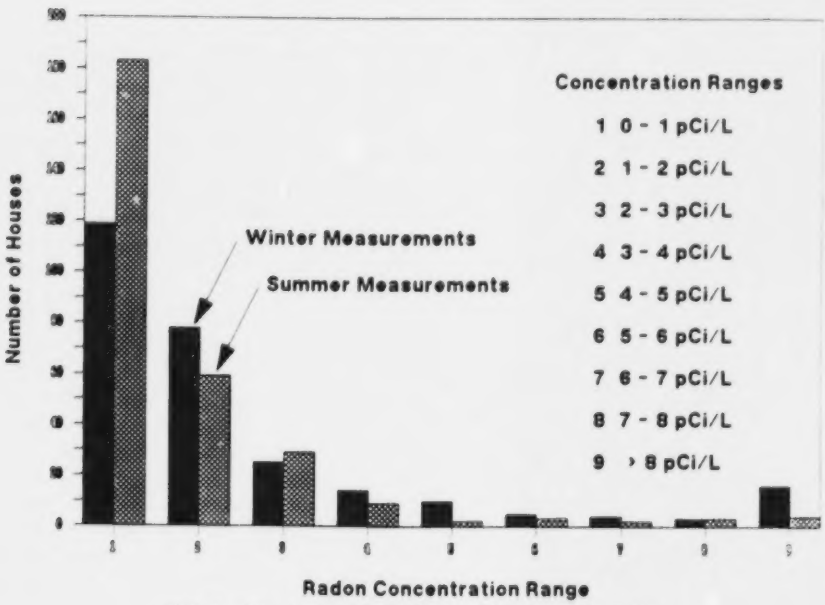
Number of Houses
Winter Measurements
Summer Measurements
Concentration Ranges
1 0 - 1 pCi/L
2 1 - 2 pCi/L
3 2 - 3 pCi/L
4 3 - 4 pCi/L
5 4 - 5 pCi/L
6 5 - 6 pCi/L
7 6 - 7 pCi/L
8 7 - 8 pCi/L
9 > 8 pCi/L
Radon Concentration Range

FIG. 6—*Distribution of preliminary radon results (pCi/L).*

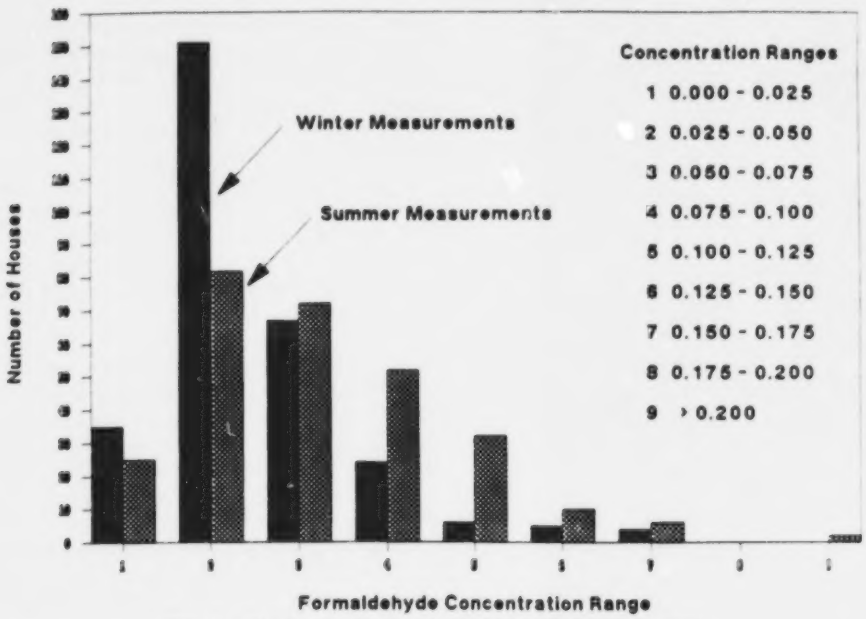

FIG. 7—*Distribution of preliminary formaldehyde results (ppm).*

impactor to estimate the extent of vapor phase loss from the filter. A subset of filter extracts were analyzed for specific PNAs using high-pressure liquid chromatography (HPLC).

The impactor sample was obtained by switching the 4 L/min pump between two impactors every 15 min. One impactor filter was returned to HSPH for analysis, and the other Teflon-PTFE filter was weighed and extracted for PNA analysis. Methylene chloride was used as the extraction solvent because it is more efficient than benzene or cyclohexane and is less toxic than acetonitrile. The extracts containing small amounts of particulate matter were removed by filtration through 0.45-μm-pore nylon membranes. In order to provide for an archival sample, an HPLC sample, and a sample for SL measurements, the filtered extracts were divided into three 5-mL aliquots and stored at −15°C. Coronene was added as an internal standard to the 5-mL aliquot used for HPLC. Figure 8 illustrates the type of differences observed from an SL analysis of samples from homes with varying amounts of PNAs. (SL response is proportional to PNA content.)

A passive PNA dosimeter developed at ORNL was used to monitor volatile and semi-volatile PNAs [*13*]. The device is self-contained, badge-sized, and light weight. No chemical extraction of the sample is required before analysis. After exposure, the dosimeter is returned to the laboratory and inserted directly into a spectrometer for analysis using the room temperature phosphorescence (RTP) technique [*14*]. One PNA dosimeter was placed in the passive sampler rack in the activity room during the first week of sampling. In a subset of houses, a second PNA dosimeter was placed in the activity room during the second week of sampling. Results from the RTP analysis provide a ranking index for the overall PNA levels in indoor air.

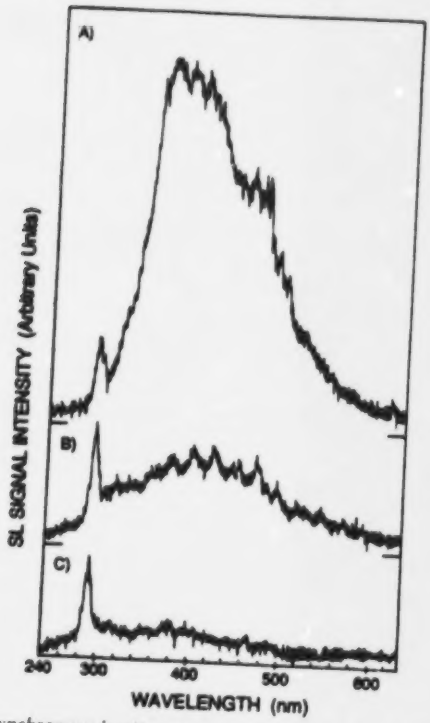

FIG. 8—*Example synchronous luminescence results from various homes. (Response "A" from home with two smokers, "B" from home without smokers, and "C" from home with electrostatic precipitator.)*

Microbial Aerosols—The Kingston/Harriman study is the first research study to comprehensively identify and quantify airborne micro-organisms in noncomplaint residences. Since little information is available on indoor concentrations of these microorganisms in homes without reported occupant complaints, this component of the supplemental indoor air quality activities provides much needed information on allergenic or pathogenic microbes in home environments. In addition to determining the total number of bacteria and fungi per unit volume of air, the resultant microbial populations were also qualitatively analyzed to determine the number and types of various genera composing the total microbial population.

Microbial content in household air was determined by sampling with the sixth stage of an Anderson impactor providing a sample of particles up to approximately 1 μm in size [*15*]. Two-minute air samples were obtained at a rate of 30 L/min. Thirty-minute samples were taken when testing for *Legionelia*. Trypticase soy (TSA), malt extract (ME), and charcoal yeast extract (CYE) agar plates were used for detection of bacteria, fungi, and *Legionella*, respectively. Blank fields samples were used with each day's supply of plates. Positive controls were used to ensure that appropriate micro-organisms would grow on each new batch of agar.

A set of TSA and ME plates were taken in the activity room and at an outside location

TABLE 4—*Summary results (CFU/m³) of viable airborne micro-organism monitoring.*

	Winter				Summer			
	Average		Range		Average		Range	
Genera	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Bacteria								
Bacillus	820	260	33–3300	0–1700	1270	600	0–6000	0–6200
Micrococcus	70	25	0–380	0–580	70	15	0–630	0–330
Staphylococcus	250	20	0–1500	0–280	140	30	0–5500	0–470
Total	1140	305			1480	645		
Fungi								
Penicillium	80	25	0–3000	0–350	870	1200	0–6200	0–8000
Aspergillus	45	15	0–450	0–270	480	340	0–3000	0–5400
Other (*Mucor, Fusarium, Candida*)	90	25	0–1300	0–220	140	100	0–1350	0–730
Total	215	65			1490	1640		

at the study homes. During the winter phase of the study, 120 homes were sampled for bacteria and fungi, with 220 homes sampled during the summer. Additional TSA and ME plates were taken at a subset of homes to test the degree of replication. After incubation, the resultant colonies were counted using a colony counter to provide colony forming units (CFU) and the genera determined by colony characteristics. Random bacterial colonies were also analyzed microscopically and, in the case of potential pathogens, enzymatically to verify colony identification. Similarly, identification of random fungal colonies was confirmed by microscopic analysis of wet mount preparations.

For *Legionella* testing in a subset of homes, hot water was collected from shower heads. In a few cases, Litton-type high-volume air samplers (HVAS) were used to collect air proximal to the showers during and immediately after discharging the hot water. The HVAS was operated for 30 min at a rate of 800 L/min. The shower water and air samples were quantitatively analyzed for *Legionella* by the direct fluorescent antibody (DFA) technique using fluorescein-labeled antisera specific for *Legionella* serogroup one or seragroups one through six.

Table 4 presents a summary of the results of the viable airborne micro-organism monitoring. Indoor concentrations were generally higher than those found in outside air. Approximately 49% of the indoor fungal samples were greater than 1000 CFU/m³, and 57% of the indoor bacterial samples were greater than 1000 CFU/m³. Substantially greater concentrations of airborne fungi were measured in both indoor and outdoor samples during the summer months. *Legionella* were not detected in a subset of 40 homes with air sampling on CYE plates but were detected by the direct fluorescent antibody test in 20% of the water samples collected. *Legionella* positive samples did not correlate with hot water temperatures but did appear more prevalent in homes with well water.

Energy Use and Weatherization Characterization

One of the objectives of the study was to characterize in detail energy use and building factors related to indoor air pollutant levels. Three specific research activities were under-

taken to evaluate these factors: home energy audits, a substudy of kerosene space heaters, and interzonal air exchange measurements.

The home energy audits were used to develop in-depth information on the characteristics of the building structure, especially as it relates to weatherization and the design and operation of the space heating and cooling system. The home energy audits also provided an important check on the information supplied by the occupant questionnaire. Trained TVA energy advisors were used to conduct the audits. A detailed survey report was made on each of the 150 residences participating in this part of the study. Over 150 separate items of data were collected on each house. In addition, floor plans (showing room dimensions and the location of duct supplies and returns) and sideviews of the audited houses were made to assist the interpretation of the indoor air quality data. The data from these audits significantly enhanced the occupant questionnaire information by providing new information on amount of insulation, weather-stripping, and storm doors and windows; the sizing and design of the space-conditioning systems in the home; and on other factors affecting crawlspace, attic, and whole house air change rates.

Kerosene heaters were an important heating source for many of the homeowners in the study and an important factor affecting the level of indoor combustion gases (particularly oxides of carbon and nitrogen). To enhance the existing data set in this area, a special research effort was sponsored by CPSC and TVA in a subset of 50 houses where kerosene heaters were used as either primary or secondary heating sources. Approximately ten weeks of NO_2 measurements using passive dosimeters were conducted in these residences. In five houses, the real-time levels of CO, CO_2, NO, NO_2, and SO_2 were examined along with room temperature profiles. Homeowners in this part of the research were asked to keep detailed records of kerosene heater usage so that a better source-term estimate could be obtained. Figure 9 gives the distribution of the estimated weekly kerosene heater usage. Figure 10 illustrates typical indoor pollutant profiles obtained.

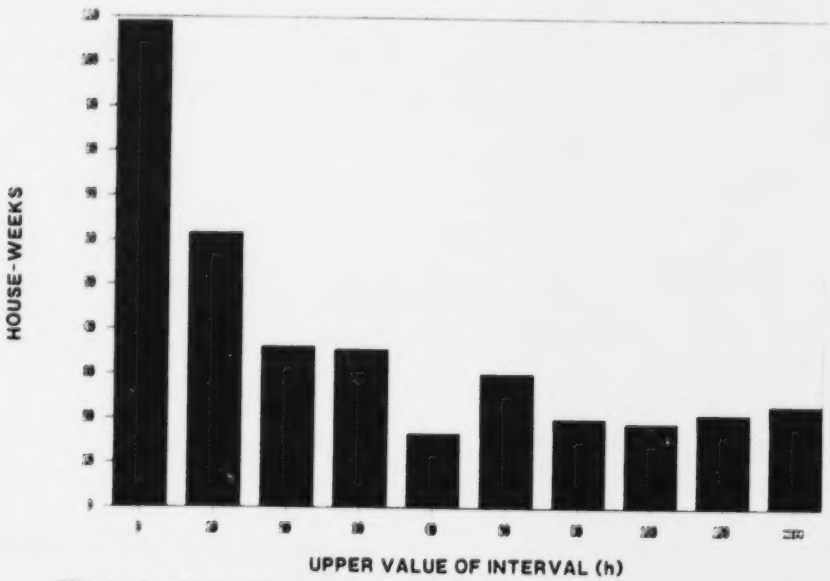

FIG. 9—*Distribution of kerosene heater use per week based on homeowner usage logs.*

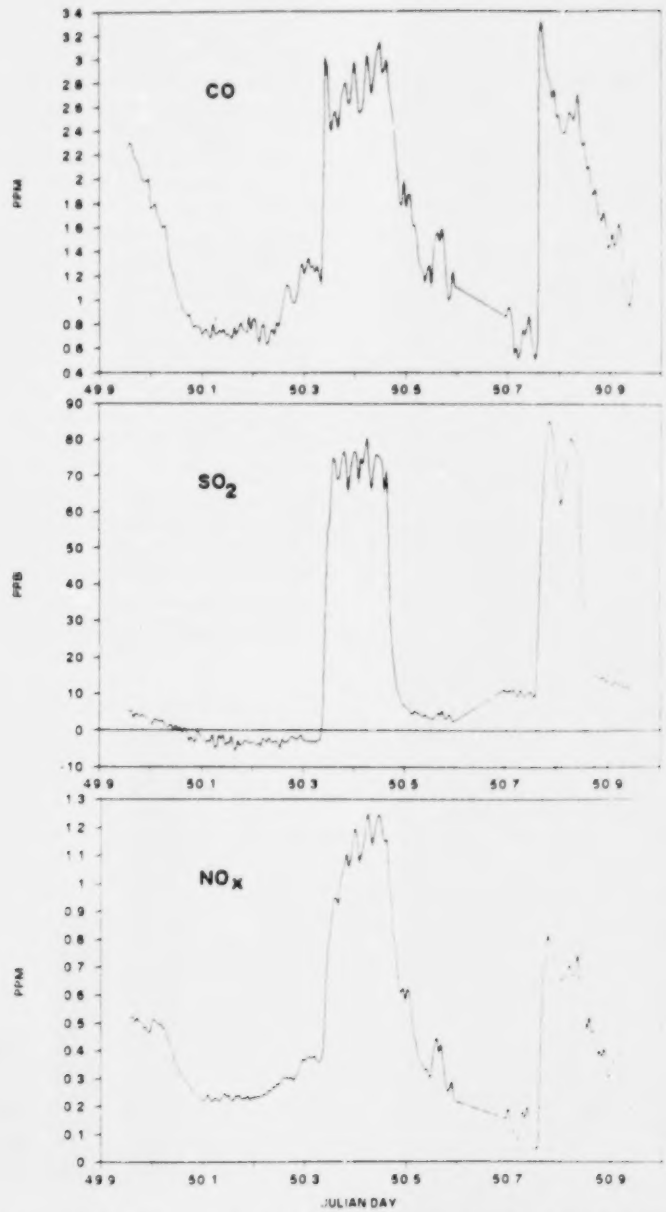

FIG. 10—*Results of real-time pollutant monitoring in room with kerosene heater in a study house.*

Interzonal mixing and air exchange rates were identified as important variables affecting the interpretation of indoor air pollutant levels related to energy use and building characteristics. To investigate these internal differences, a second source with a different type of perfluorocarbon tracer was placed in each house. In a subset of the houses, both tracer gas concentrations will be analyzed by HSPH to estimate the degree of zone mixing and external air exchange.

Remaining Work

A substantial amount of data on a wide range of pollutants, as well as over 20 pages of information on occupant behavior and house characteristics per house, have been collected in the Kingston/Harriman study. Much of these data have just recently been quality control checked, and some samplers are yet awaiting laboratory analysis. Further results will be forthcoming on PNA concentrations, air exchange rates and internal mixing, and the degree of house weatherization in the homes, as well as information on the respiratory health of the participants and questionnaire data on occupant behavior and housing characteristics. These extensive data sets provide an invaluable opportunity to investigate the relationships among a broad range of parameters.

Summary and Lessons Learned

Although additional analyses are yet to be completed, there are several conclusions that can be drawn from this study. The range of indoor pollutants investigated represent one of the most extensive characterizations of indoor air quality ever investigated in a large number of homes. The effectiveness of complementary research components supported by several sponsoring organizations was successfully demonstrated, thus encouraging continued optimization of limited resources for indoor air quality research from both the public and private sectors. The total information gained by the concurrent investigations should prove much more valuable than from separate isolated studies.

Preliminary analyses of the pollutant monitoring results indicate that the majority of the nitrogen dioxide levels were less than 20 ppb with a higher proportion of winter phase results greater than 30 ppb than for the summer phase. Similar distributions of RSP concentrations were obtained for winter and summer phases, most of the results being less than 50 $\mu g/m^3$. Relatively tight distributions were obtained for water vapor compared to pollutant levels, with lower winter values than summer, as expected. Relatively few houses were found to have radon levels greater than 4 pCi/L; a slightly higher distribution was obtained in the winter compared to the summer. In contrast to most other pollutants, formaldehyde levels were higher in summer than winter, consistent with higher temperature and water vapor levels in summer, which are known to increase major formaldehyde source emission rates. Relatively few concentrations were greater than 0.1 ppm. Results for PNA levels are incomplete, although preliminary results indicate that homes with smokers have higher mean levels than other homes. Lower levels of airborne fungi were found in winter than summer. Airborne bacterial levels were frequently greater than 1000 CFU/m^3 in both seasons, while during the summer the airborne fungi levels were frequently greater than 1000 CFU/m^3.

This study also demonstrated that, by careful planning and attention to the burden placed on homeowners, researchers can gain the participants' willing concurrence for an extensive indoor air quality characterization. Table 5 presents results of a post-study evaluation survey conducted of participants. As shown by these results, there is a clear feeling that the study was positively received and that homeowners would willingly participate again.

The importance of developing and implementing an effective data management plan

TABLE 5—*Results from a post-study evaluation survey.*

1. Did we explain the purpose of the study adequately?						
(not at all)	1	2	3	4	5	(very thoroughly)
	(1)	(1)	(11)	(42)	(101)	
2. Did our air samplers disturb you?						
(not at all)	1	2	3	4	5	(very much)
	(109)	(23)	(13)	(7)	(5)	
3. Overall, did you enjoy being in the study?						
(I hated it)	1	2	3	4	5	(I had a great time)
	(0)	(5)	(29)	(43)	(80)	
4. Would you participate now that you know what it is about?						
(definitely no)	1	2	3	4	5	(definitely yes)
	(2)	(3)	(19)	(25)	(107)	

cannot be overstated. Sufficient experimental uncertainty exists without the need to introduce additional variability into the analysis through problems with data handling. The following discussion identifies some important recommendations for a good data management program for large indoor air quality field studies.

A central factor governing the quality of the data management program is the structure of the field data entry forms. These forms should be designed to ensure ease of entry by those who will eventually keyboard the data. Forms should be field tested before they are extensively adopted to make certain they provide adequate definitions, are appropriate for the range of data that will be collected, and are clear for all users. Because of the need to correlate many different variables in indoor air quality investigations, the use of relational data base structure is recommended. Also, this type of data structure will give greater flexibility to the data management system if new data categories need to be added as the study progresses. Errors are unavoidable in any large-scale data entry operation. To expedite data checking or verification, programs should be developed to verify data entry operations. The first type of program should be one which checks the validity of each entry against an expected range for that parameter. This should be done on-line to make identification and correction more efficient. A compare program is another type of validation program for quality control checks of data entry operations.

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The researchers wish to thank the various sponsors and project officers who have made possible this comprehensive characterization of indoor air quality in the study homes. Without this concerted effort, the necessary support to conduct the study would not have been possible. Recognition is extended to the field team who spent many late evenings to accommodate homeowner schedules. Their conscientious efforts and thoughtful interactions with study participants were critical components to the study success. Final thanks and

recognition go to the study participants for their willingness to contribute to this advancement of science.

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